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Closure in the Earth's angular momentum budget observed from subseasonal periods down to four days: No core effects needed

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[1] Short period variations in the Earth's rotation rate, length-of-day (LOD), are driven mainly by the atmosphere with smaller contributions by the oceans. Previous studies have noted a lag of atmospheric angular momentum (AAM) with LOD that would imply another source. We examine AAM from the European Centre for Medium-Range Weather Forecasts (ECMWF) and the National Centers for Environmental Prediction (NCEP) reanalysis series, along with oceanic angular momentum (OAM) from the ECCO consortium; land hydrological effects made no discernible impact. The NCEP reanalysis together with OAM produces a significant lag with LOD, while the ECMWF reanalysis AAM with OAM shows no phase lag. We find significant coherence with LOD variations down to periods of 4 days; coherence losses at shorter periods likely arise from the inverted barometer assumption and unmodeled dynamical processes. Thus the inclusion of core effects is not needed to balance the axial angular momentum budget on sub-seasonal time scales.
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1. Introduction

[2] The rotation rate of the solid Earth (crust and mantle) is affected by exchanges of angular momentum with adjacent geophysical fluids (the core, oceans, land hydrology and atmosphere), as well as gravitational torques from external bodies (in particular the Moon and the Sun [*Hide and Dickey*, 1991; *Rosen*, 1993]). For the atmosphere, variations in axial angular momentum are dominated by changes in zonal flow speeds (the wind term), with the effect of mass redistribution (the pressure term) being an order of magnitude smaller [*Rosen et al.*, 1990; *Dickey et al.*, 1992]. The ocean contributions, while smaller than the pressure term, are also significant in the closure of the axial angular momentum budget [*Marcus et al.*, 1998]. Early studies showed that LOD and AAM were coherent down to periods of 14 days [*Rosen et al.*, 1990]; later work demonstrated that with improved tidal modeling the coherence limit can be extended down to 8 days, with the loss of coherence at shorter periods attributed to noise sources in both data types [*Dickey et al.*, 1992]. At the same time, phase discrepancies between AAM and LOD at periods up to 100 days had been noted [*Zatman and Bloxham*, 1997; *Zatman*, 2001] and used to argue for the rotational effects of a third angular momentum reservoir, in particular the Earth's core, on subseasonal time scales. While changes in core angular momentum (CAM) have been shown to contribute to Earth rotation fluctuations on decadal and longer time scales [*Hide et al.*, 2000], core influences at shorter periods remain controversial [*Holme and de Viron*, 2005, and references therein]. In this study, we examine atmosphere-ocean forcing of Earth rotation on synoptic to intraseasonal time scales in greater detail, in order to determine whether influences from the core are implied by unresolved phase discrepancies with the LOD, and to assess the impact of more recent data on the high-frequency coherence limit and the reasons for loss of coherence at shorter periods.

2. Data Considered

[3] The effect of the geophysical fluid layers on the LOD is derived from the theorem of angular momentum (AM) conservation; we estimate the AM of the individual fluids (atmosphere, ocean and land hydrology; see Table 1), and consider that any change of the total AM of the fluid layers has to be compensated by a change of the AM of the solid Earth (crust and mantle), and consequently of its rotation. The AM of the fluid layers is estimated from velocity fields (wind or current) and pressure fields (Earth surface or ocean bottom) coming from atmosphere and ocean global circulation models (GCMs). The AM also includes hydrological loading of the Earth's surface, but we found it to have no discernible impact on our results. For the ocean, the axial AM time series from the ECCO model, which assimilates TOPEX/POSEIDON altimeter and other data types, has been used [*Fukumori*, 2002]. The atmosphere has been accounted for using AM time series from two different GCMs: the U.S. NCEP and the European ERA [*Salstein et al.*, 1993]. Both are reanalyses (long term assimilations with a "frozen" atmospheric model) incorporating grid-resolved dynamics and parameterized representations of sub-grid scale processes such as convection and turbulent mixing. The NCEP model extends from the surface to 10 hPa [*Zhou et al.*, 2006], whereas the ERA model reaches the 1 hPa level. The tide-corrected LOD data were taken from the Kalman-filtered SPACE2007 series, which incorporates high-temporal resolution GPS observations from the Inter-

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Table 1. Data Used in This Study

Subsystem	Data Type	Data Set	Spatial Domain	Time Period Used
Atmosphere	AAM	ERA40	Surface to 1 hPa	Jan 1993 to Aug 2002
Atmosphere	AAM	NCEP1	Surface to 10 hPa	Jan 1993 to Aug 2002
Atmosphere	AAM	NCEP2	Surface to 10 hPa	Sep 2002 to Mar 2006
Land Hydrology	HAM	NCEPH	Excludes polar ice sheets	Jan 1993 to Mar 2006
Mantle (Length-of-day)	LOD	SPACE2007	Global Kalman-filtered solution	Jan 1993 to Mar 2006
Ocean	OAM	ECCO (kf049f)	Excludes Arctic Ocean	Jan 1993 to Mar 2006

national GPS Service along with data from other space-geodetic observational networks [*Ratcliff and Gross*, 2009].

3. Results and Discussion

[4] Considering the solid Earth-ocean-atmosphere system as isolated (the tidal effect on the LOD was subtracted from the observed values), fluctuations of the LOD can be inferred from the total angular momentum of the fluid layers (AAM + OAM). The comparison of these series is a good indicator of (1) the quality of the observations and their processing and (2) the degree of dynamical closure of the system. Figure 1a shows the results of coherence phase analysis of the LOD data with various AAM series, with (solid lines) and without (dashed lines) the OAM effect, respectively, for periods up to 100 days. The results for NCEP AAM during the period of overlap with the ERA40 data (1993–2002; dashed black line) show considerable phase discrepancy with LOD, generally increasing with period up to 100 days; the addition of OAM reduces the phase lag somewhat (solid black line), but still leaves it highly statistically significant, as shown by the individual error bar centered on the combined phase lag at 55 days. Similar results from earlier NCEP AAM series led *Zatman and Bloxham* [1997] to speculate on possible CAM contributions to LOD on these time scales; the AAM-LOD phase discrepancy implied by their three-component atmosphere-solid Earth-core model (heavy green line) agrees fairly well with the NCEP results shown here.

[5] By contrast, the phase for the ERA40 AAM during the same period (dashed blue line) is consistent with zero discrepancy, and with the addition of the OAM values (solid blue line), appears to agree within the uncertainty (illustrated by the individual blue error bar) with the LOD phase at periods up to 100 days. For the more recent (2002–2006) NCEP data that we examined, the AAM phase discrepancy (dashed red line) is considerably smaller than obtained for the earlier NCEP data; again the OAM values tend to make the phase more similar to the LOD (solid red line), although the difference is still statistically significant (as indicated by the individual red error bar). Enhancement of the earlier NCEP AAM series with ERA40 winds above 10 hPa produced no significant change in the NCEP phase discrepancy (not shown); similarly, addition of the NCEP hydrological forcing provided no significant phase effects (not shown).

[6] The lag-lead structure of the data may also be visualized by examining the correlation between band-pass filtered LOD and various angular momentum series as a function of period (Figure 1b). While the earlier NCEP data (top row) show a clear tendency towards positive lag with respect to LOD as the period increases, this phase bias is less pronounced for the more recent NCEP series (middle row), particularly for periods greater than 60 days. By comparison the ERA40 results are nearly symmetrical with respect to the sign of the lag (bottom row), with the addition of OAM further concentrating the high correlation amplitudes about the zero lag axis.

[7] Figure 2 shows the LOD coherence amplitude for the three AAM series considered from the Nyquist period (2 days) to 20 days, with the contributions from ECCO-modeled OAM included. It is interesting to note that each series shows a sharp drop in coherence at periods of about 4 days (a reduced coherence observed for all series at 9.13 days, although still >95% significant, indicates that the model for the 9.13 day tide needs to be improved). The differences from earlier results (e.g., 8-day limit given by *Dickey et al.* [1992]) attest to improvements in the observations and analyses used to produce the more recent atmospheric data, as well as the inclusion of ocean model results and the incorporation of high temporal resolution GPS data into the LOD estimates (see *Ponte and Ali* [2002] for results using altimeter-optimized barotropic ocean modeling). The similar high-frequency cutoff found for our data sets, notwithstanding their different origins and time spans, suggests that the loss of coherence at periods of about four days may represent a dynamical effect not accounted for in the models used here, rather than declining high-frequency signal-to-noise ratios in the geodetic or geophysical data involved (see *Dickey et al.* [1992] for discussion of these issues).

4. Summary and Conclusions

[8] We examined the coherence phase and amplitude between LOD and various series of AAM, including the effects of ECCO-modeled OAM, in order to (1) evaluate the robustness of a previously-reported phase lead of LOD with respect to atmosphere-ocean excitation, which has been used to argue for core effects on Earth rotation at intraseasonal periods, and (2) re-visit the high-frequency coherence limit between LOD and its excitation sources, in the light of possible dynamical contributions to the loss of coherence with LOD at synoptic periods.

[9] Our results indicate that the phase lead observed for LOD may reflect data quality, modeling and analysis issues rather than core effects, since it is absent when using AAM computed from the ERA40 product of the ECMWF reanalysis in combination with ECCO-modeled OAM, and is reduced when using more recent NCEP data. The common loss of coherence at periods near 4 days for the three AAM series analyzed here in combination with ECCO OAM suggests the presence of dynamical effects not accounted for in the atmosphere-ocean models employed to calculate the angular momentum forcing of LOD. A known dynamical shortcoming of the models used here is the breakdown of

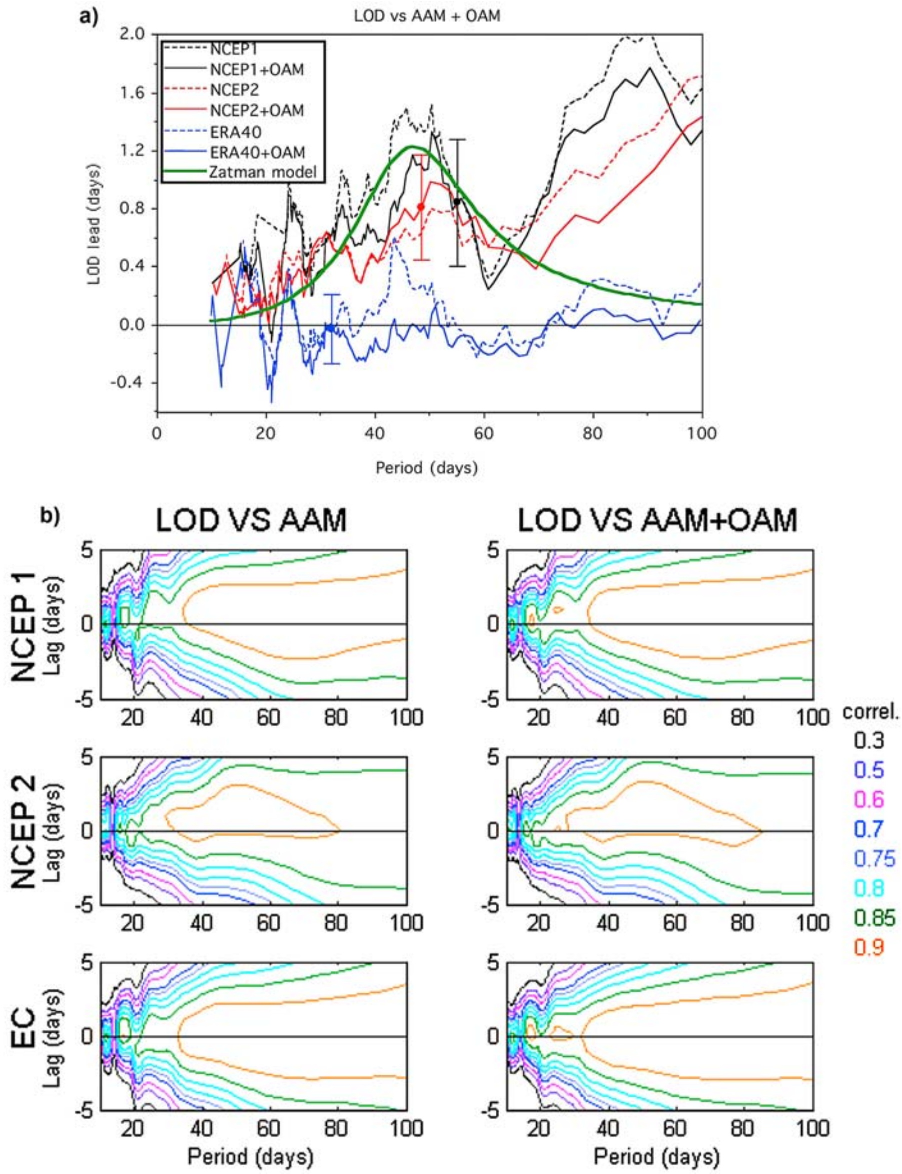

Figure 1. (a) The coherence phase between the LOD and its excitation by different AAM series (including wind and IB pressure forcing, dashed lines) and by the AAM series combined with ECCO-modeled OAM contributions (including current and pressure terms, solid lines). Results using the NCEP and ERA40 reanalysis values for the period January 1993 to August 2002 are shown by the black and blue lines, respectively, while NCEP values computed for the later period September 2002 to March 2006 are shown by red lines; illustrative values of the uncertainty (1-sigma) are shown by individual error bars for each of the combined series. Heavy green line shows LOD phase lead due to core effects as specified by the three-component model of *Zatman and Bloxham* [1997]. (b) Correlation between band-passed values of (left) LOD and AAM or (right) AAM + OAM for (top) NCEP from 1993 to 2002, (middle) NCEP from 2002 to 2006, and (bottom) ERA40 from 1993 to 2002 as a function of period and lag.

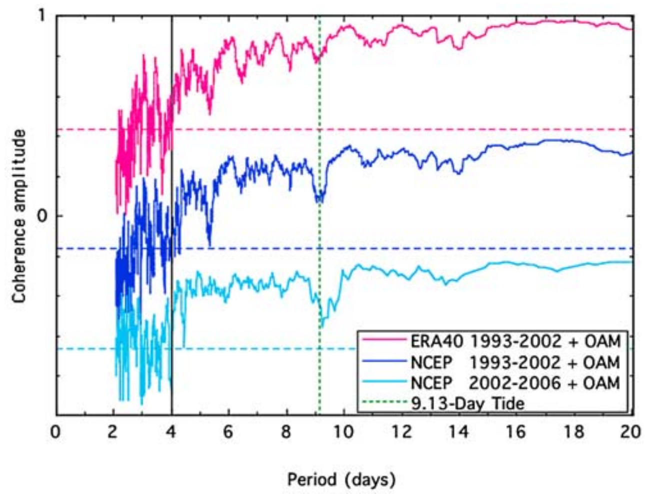

Figure 2. The coherence amplitude between the LOD and different AAM series combined with OAM (solid lines); successive series have been shifted downwards by an amplitude offset of 0.6 for ease of viewing. The 95% confidence levels are shown by dashed lines of the same color; note the general loss of coherence at periods below approximately 4 days (solid black line) and the reduction of coherence (still significant at the >95% level) near the tidal period of 9.13 days (dotted green line).

the IB assumption at synoptic periods, as exemplified by an observed non-isostatic 5-day variability that has been reported in the oceanic response to global-scale atmospheric disturbances [*Ponte and Vinogradov*, 2007, and references therein; *Hirose et al.*, 2001]. *Ponte and Ali* [2002] explored the contribution of non-IB processes using a barotropic ocean model; however, further work is needed with more realistic models. Another possible source of inaccuracy in the models is poorly resolved topography; high frequency fluctuations likely have small length scales that are more susceptible to short-range topographic effects for both the atmosphere and ocean. Our results indicate that ongoing improvements in model resolution and accuracy, including simulation of the pressure-forced dynamics of the ocean in full-physics models, can be expected to further reduce and eventually eliminate phase and amplitude discrepancies in the LOD response to atmosphere-ocean forcing on synoptic to intraseasonal time scales, without the need to invoke core effects.

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